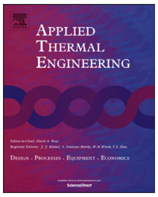
Applied Thermal Engineering 74 (2015) 83–88

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng



Torrefaction: Unit operation modelling and process simulation

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ARTICLE INFO

Article history:
Received 9 September 2013
Accepted 24 December 2013
Available online 3 January 2014

Keywords:
Torrefaction
System integration
Cycle Tempo®

ABSTRACT

Torrefaction, a mild form of pyrolysis is seen as an effective means of ameliorating the properties of raw biomass for subsequent thermal conversion, especially in applications such as large scale co-firing with coal. Even as the chemistry of torrefaction reactions have been studied in the past, the thermodynamic analysis of the torrefaction process is critical in assessing its viability, which is the objective of the present study.

The system analysis software Cycle Tempo® is used to simulate a steady state model of the torrefaction process by linking unit operation blocks of drying and torrefaction along with auxiliary process equipment. The process is simulated for different cases of inputs where it is observed that the system efficiency decreases with increasing torrefaction temperatures and increasing biomass moisture content. It can also be seen that the low temperature heat exchanger associated with the drying process carries the highest heat load in the system.

The developed tool can be used in designing the process flow and a realistic heat integration strategy with a view to feasible sizing of process equipment.

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1. Introduction

1.1. Background

Torrefaction is a pre-treatment technology aimed at processing biomass fuels to facilitate or enable their use in thermochemical processes. It is a mild form of pyrolysis, where biomass is subjected to temperatures around 230–300 °C in a non-oxidizing atmosphere. From the perspective of ultimate analysis, biomass fuels preferentially lose oxygen and hydrogen, resulting in a transformation of biomass into a coal-like solid [1]. On a compositional basis, this is related to the devolatilisation of the hemicellulose fraction (and possibly a partial degradation of cellulosic and lignin fractions) of biomass [2]. In addition to improving combustion properties (increased calorific value and adiabatic flame temperatures) and reduced volatility, torrefaction also leads to increased hydrophobicity, better grinding and decrease in biological degradation activity [1–3]. The degree to which the biomass properties are altered depends on the so-called “severity” of torrefaction, which relates to the residence times and temperatures used in the process.

Kinetics of torrefaction reactions have been studied extensively in the past. Torrefaction is reported to have energy yields ranging from 75 to 90% for mass yields around 50–70%, depending on the severity of the torrefaction reaction [3,4]. The present study, however, aims at a holistic analysis of the torrefaction system towards identifying process design bottlenecks and assessing the efficiency of the torrefaction. A few studies have been performed [5,6] in the past which deal with a system study of torrefaction, however this study additionally takes into account the change in unit operations (drying/torrefaction reactor) response to differing conditions of temperatures, residence times and mass flows. The aim of this study is to design a tool to enable us in identifying the range of operational parameters for which torrefaction can be carried out optimally.

1.2. Process heat requirement

In addition to the sensible heat required to raise the temperature of the biomass to torrefaction temperatures, a significant amount of heat is required to evaporate the water contained in the biomass. Various studies cite torrefaction reactions as being mildly endothermic or exothermic depending on the extent of reaction [7]. Even as the heat of reaction may be an important variable with respect to process control, it is not a primary heat source or heat sink with respect to the entire process.

The heat requirements for the torrefaction process can be summarized as: 1) A large quantity of heat at a relatively low temperature for drying biomass, 2) a small quantity of heat

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http://dx.doi.org/10.1016/j.applthermaleng.2013.12.059

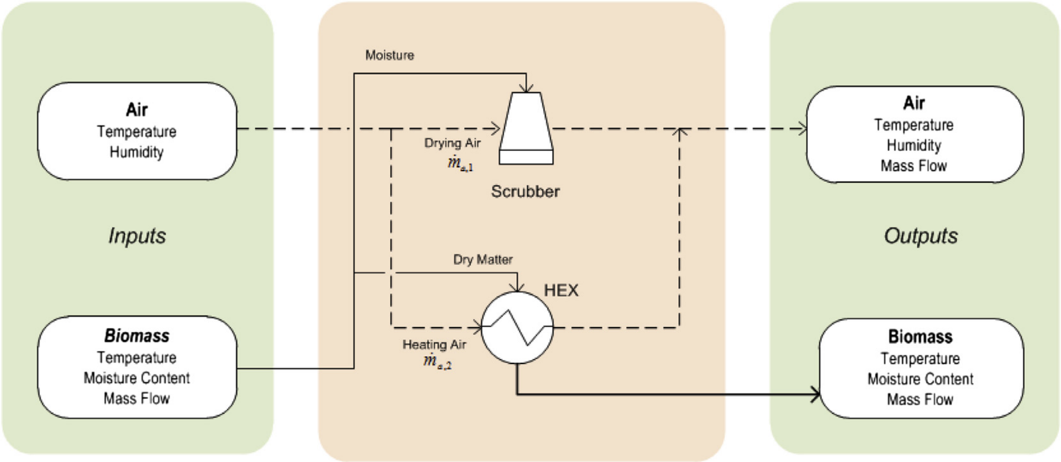

Fig. 1. Dryer schematic.

required to raise and maintain the temperature of biomass at the torrefaction temperature.

On the other hand, the heat required by a unit operation can be supplied by either 1) combusting additional fuel, 2) combusting the torrefaction gases or 3) recirculating heat. In a stand-alone torrefaction plant, the heat supplied by torrefaction gases may need to be supplemented by additional fuel firing for successful operation. Since supplementary fuel firing represents an escalation of costs, it has been suggested that the torrefaction process can be integrated with existing waste heat sources [5]. However, the integration between a primary process operation and the torrefaction unit should be designed in a manner that ensures that operation of the primary process resulting in the waste heat source is not hindered. Furthermore, a system integration may also lead to better utilization of the torrefaction gases in addition to heat recirculation helping to minimise the total external heat required.

The present study aims at developing a tool to design and optimise a torrefaction process operating in conjunction with a waste heat source with respect to maximizing system efficiency.

2. Modelling of unit operations

2.1. Dryer

An ideal direct contact convective dryer has been used for achieving easier and more uniform heat transfer to the bulk of solids. It is assumed that the dryer completely evaporates the moisture contained in the biomass with a convective heated air flow. The air flow cools as it passes through the dryer and is assumed to be saturated at the dryer exit.

The dryer model takes in the mass flow and inlet conditions of the solid (temperature, moisture content) and the inlet conditions of the air (temperature, moisture content) as inputs and yields the required mass flow rate of air for complete drying as the output.

The dryer has been modelled in Cycle Tempo® as a combination of a co-current heat exchanger and a scrubber (a co-current saturator) as shown in Fig. 1. The two effects of water evaporation and solid matter drying are modelled separately along with their respective convective media (drying air/heating air), subject to the same initial conditions.

The Cycle Tempo® model scrubber is used to simulate the saturation of the convective medium (drying air) with moisture evaporating from the biomass, subject to the boundary condition that the temperature of the air leaving the dryer is same as the temperature of the non-evaporated water. For a given air inlet temperature, the mass flow of drying air is iterated to achieve complete dry out of the contained moisture, $\dot{m}_{a,1}$.

The outlet temperature of the drying air is then used as the outlet temperature of the dry biomass as well as the outlet temperature of the heating air. This leads to the calculation of the heating air flow, $\dot{m}_{a,2}$ through the heat exchanger that is in thermal equilibrium with the drying air flow, $\dot{m}_{a,1}$.

The net mass flow of air in the dryer is hence given by $\dot{m}_a = \dot{m}_{a,1} + \dot{m}_{a,2}$.

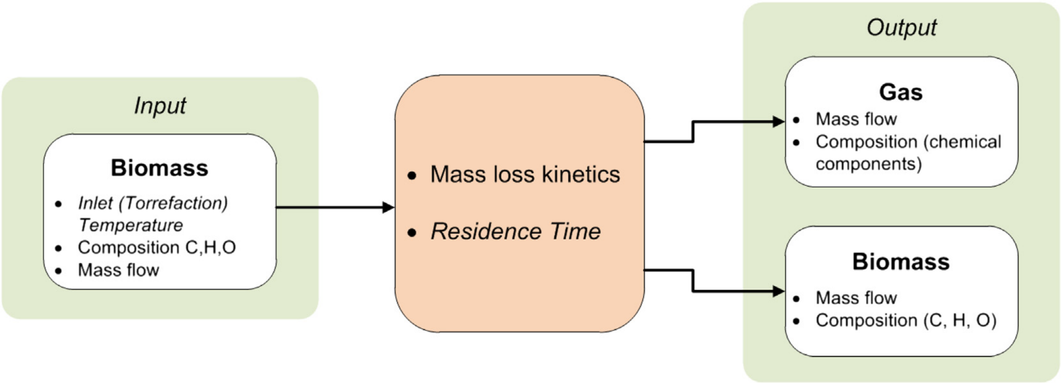

Fig. 2. Torrefaction reactor schematic.

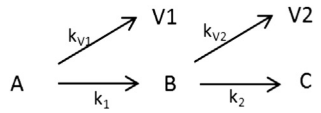

Fig. 3. Two-step reaction scheme based on pseudo-components.

2.2. Torrefaction reactor

The torrefaction reactor as shown schematically in Fig. 2 takes in the mass flow, composition and inlet temperature of the dry biomass as inputs and generates the composition and yields of torrefaction gases and solids as outputs. The torrefaction reactor is programmed in Matlab® with torrefaction kinetics for a specific biomass with residence time and torrefaction temperature as variables. It is assumed that reaction kinetics limit the progress of torrefaction. It is further assumed that the heating up of the biomass is rapid and that the torrefaction reactions are predominantly carried out at an isothermal torrefaction temperature.

The two-step kinetic reaction using pseudo-components (Fig. 3) has been used [8] to model weight loss in torrefaction. However, for the purpose of modelling the complete process, in addition to the weight loss kinetics, it is also essential to identify the volatile streams with respect to their chemical composition and calorific values. The approach proposed by Bates and Ghoniem [4] is used for this purpose. Reaction rate constants are modelled using an Arrhenius equation which has been fitted to experimental data for a particular type of biomass. Consequently, the solid and volatile yields and their respective compositions are functions of temperature as well as residence time.

The higher heating values of the solids are calculated by on the basis of the elemental (C, H, O) composition using the correlation given in Friedl et al. [9]. The higher heating values of the torrefaction gas are determined by a weighted average of the higher heating values of its components. As stated in Section 1.2, the torrefaction process is considered to be autothermal and no effect of sensible heating of the reaction products is accounted for.

3. Process modelling

The process model as shown in Fig. 4 consists of a dryer and torrefaction reactor in series. The waste heat source is assumed to be superheated moderate pressure steam, which delivers heat to the process via counter-current high temperature (HT) and low temperature (LT) heat exchangers. The high temperature heating source supplies the necessary sensible heat to heat up the dried biomass to torrefaction temperatures. It is assumed that the temperature difference at the high temperature side of the HT heat exchanger is 25 °C. The low temperature heating source is used to heat a convective medium (air) that is used as a heat and mass transfer medium in the biomass dryer. The large heat requirement for drying is fulfilled utilizing the latent heat of condensing steam in the LT heat exchanger at saturation temperature. For steam at 8 bar, the maximum temperature air temperature so obtained is around 170 °C (corresponding to the steam saturation temperature at that pressure). It is assumed that the system integration allows the extraction of steam with varying degree of superheat from the primary process as well as the return of used wet steam.

Following torrefaction, the hot solids are cooled with cold air in a counter-current heat exchanger; resulting in the cold air scavenging a part of the heat prior to entering the LT heat exchanger. It is assumed that the temperature difference at the low temperature side of the cooler is 25 °C. The torrefaction gas may be (co-) combusted which provides an additional source of heat.

The process modelling of the torrefaction system is carried out using the software Cycle Tempo® developed in the Process & Energy Department of the Delft University of Technology. The dryer and torrefaction unit operations which are programmed separately are modelled as generic sources and sinks of process streams. The values obtained from these blocks are given as inputs to the Cycle Tempo® model. Fig. 5 shows a screenshot of the Cycle Tempo® simulation.

Model inputs used for the simulations are given in Table 1.

The torrefaction temperature is varied (250 °C, 270 °C, 290 °C) in the simulations to understand its influence on the output. It may be noted that temperatures cases lower than 250 °C have not been considered in the simulations since hemicellulose degradation is negligible and these cases cannot be considered as torrefaction processes with respect to upgrading of feedstock. Also, the moisture content of biomass is varied (20%, 30%, 40% wet basis) for a given dry biomass flow rate and torrefaction temperature to understand the effect of dryer load on system efficiency.

4. Results and discussion

The model is first simulated for various cases of torrefaction temperatures for a typical residence time of 30 min. The results obtained from this simulation are shown in Table 2.

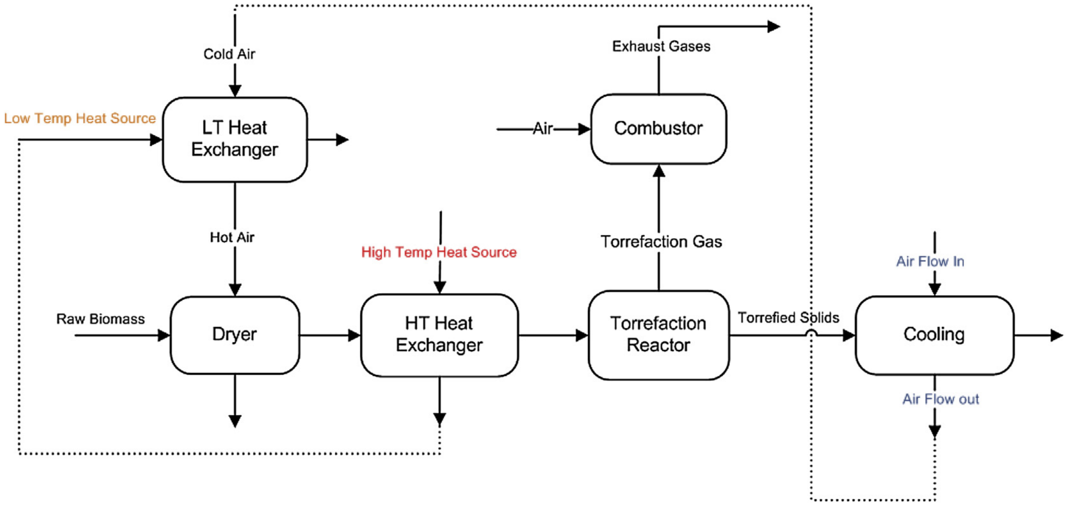

Fig. 4. Torrefaction process scheme.

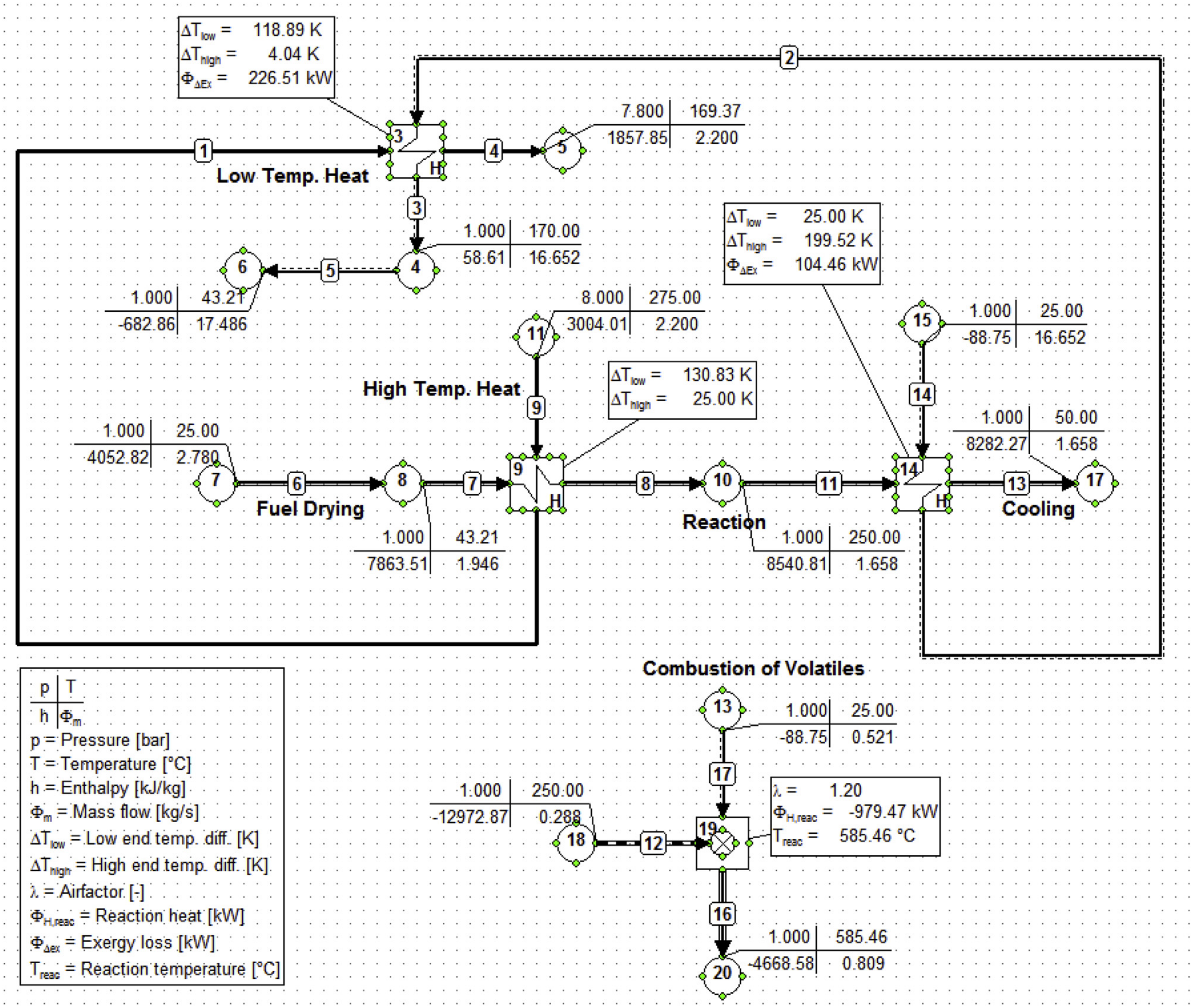

Fig. 5. Torrefaction model on Cycle Tempo® GUI (at torrefaction temperature of 250 °C).

Table 1
Model inputs for Cycle Tempo®.

Model constants	Value
Operating pressure	1 bar
Waste steam pressure	8 bar
Air	
Inlet temperature	25 °C
Inlet relative humidity	60% (at 15 °C)
Biomass	
Mass flow rate	1.946 kg/s (dry)
Inlet temperature	25 °C
Dryer	
Relative humidity in gas outlet	99%
LT heat exchanger	
Drying air inlet temperature	170 °C
HT heat exchanger	
ΔT_H	25 °C
Cooler	
ΔT_L	25 °C
Torrefaction reactor	
Residence time	30 min

The net heat that can be obtained from the fuel is seen to decrease since the energy loss on account of the solid mass loss cannot compensate for the increase in calorific value. Even as lower temperatures lead to increased energy output, this “optimum” does not account for the maximization of other desirable properties of torrefied biomass (e.g. improved grindability or storability), which is likely to happen at higher temperatures.

The dryer performance does not change with the torrefaction temperatures for a constant inlet moisture content of the biomass. Hence the drying air flow rate is seen to be constant over the range of torrefaction temperatures. The maximum temperature of the waste heat source increases from 275 °C to 315 °C due to the high end temperature difference assumption for the HT heat exchanger. Consequently, we can see that the heat transferred at the HT heat exchanger increases by up to 20% over the given temperature range. As is expected for a torrefaction process, the mass flow of the torrefied biomass decreases with increasing temperatures due to a greater extent of volatilization. This has an effect on the amount of heat scavenged in the cooler, which leads to a drop in the air inlet temperatures for the LT heat exchanger which in turn leads to a slightly higher LT heat exchanger duty. In all it can be observed that over the range of torrefaction temperatures, the net heat supplied to the process increases by around 7%.

Table 2
Effect of varying torrefaction temperatures (30% moisture content).

	Torrefaction temperatures (°C)		
	250	270	290
Raw biomass flow (kg/s)	2.78		
Dry biomass flow (kg/s)	1.946		
Drying air flow rate	16.652		
Torrefaction products			
Solid yield %	85.22%	74.54%	59.28%
Solids flow (kg/s)	1.658	1.451	1.154
HHV (solids) (MJ/kg)	20.924	22.754	25.786
Volatile flow (kg/s)	0.288	0.495	0.792
HHV (volatile) (MJ/kg)	4.241	4.808	5.760
Steam conditions			
Inlet pressure (bar)	8	8	8
Inlet temperature (°C)	275	295	315
Inlet heat rate (MW)	6.378	6.471	6.564
Outlet heat rate (MW)	3.853	3.881	3.870
Net heat rate	2.525	2.590	2.694
Heat transfer (MW)			
Low temperature HEX	2.025	2.040	2.093
High temperature HEX	0.500	0.550	0.600
Cooling HEX	0.429	0.414	0.360
Heat potentials (MW)			
Torrefaction gas	1.220	2.382	4.564
Torrefied fuel	34.700	33.006	29.748
System efficiency with torrefaction gas combustion	92.44%	90.92%	87.92%
System efficiency without torrefaction gas combustion	89.31%	84.80%	76.23%

We now define a system efficiency as the ratio of total (potential) thermal output to the thermal input inputs. The efficiency as Equation (2) contains the potential heating value of the torrefaction gases in addition to the factors in Equation (1).

$$\eta_{\mathrm{I}} = \frac{\mathrm{HHV}_{T,s} \times \dot{m}_{T,s}}{\mathrm{HHV}_R \times \dot{m}_{T,s} + \Delta H} \tag{1}$$

$$\eta_{\mathrm{II}} = \frac{\mathrm{HHV}_{T,s} \times \dot{m}_{T,s} + \mathrm{HHV}_{T,g} \times \dot{m}_{T,g}}{\mathrm{HHV}_R \times \dot{m}_{T,s} + \Delta H} \tag{2}$$

Where:

$\mathrm{HHV}_{T,s}$ ≡ Higher heating value of the torrefaction solids
$\mathrm{HHV}_{T,g}$ ≡ Higher heating value of the torrefaction gas
HHV_R ≡ Higher heating value of the raw biomass
$\dot{m}_{T,s}$ ≡ Mass flow of the torrefaction solids
$\dot{m}_{T,g}$ ≡ Mass flow of the torrefaction gas
ΔH ≡ Net heat input

Table 3
Effect of varying moisture content (torrefaction temperature: 270 °C).

	Moisture content (wet basis)		
	20%	30%	40%
Dry biomass flow (kg/s)	1.946		
Raw biomass flow (kg/s)	2.433	2.780	3.243
Water removed (kg/s)	0.487	0.834	1.297
Drying air flow rate	10.09	16.65	25.45
Heat transfer (MW)			
Low temperature HEX	1.07	2.04	3.34
System efficiency with torrefaction gas combustion	93.25%	90.92%	88.00%
System efficiency without torrefaction gas combustion	86.98%	84.80%	82.08%

Table 4
Design parameters for heat exchangers [torrefaction temperature = 270 °C, moisture content (wet basis) = 30%].

	Terminal temperature difference (°C)		U*A (kW K^{-1})
	High side	Low side	
Low temperature HEX	11	120	44
High temperature HEX	25	140	8
Cooling HEX	220	25	4

As we can see from Table 2, the efficiency values of torrefaction process are seen to decrease with increasing torrefaction temperatures, with an increasing spread in the values of η_{I} and η_{II} owing to the improving quality and quantity of torrefaction gas.

Table 3 shows the variation of process parameters with varying moisture contents (20%, 30% and 40% on a wet basis) for the same dry solid flow. It can be seen that the LT heat exchanger load increases with higher moisture contents, leading to a small decrease in system efficiency. It must be emphasised that these efficiency values do not account for the variation in the quality of waste heat required and rejected by the process, which is of significance in the overall optimization of the process. However, this value is dependent upon the efficiency and means of production and utilization of the heating media in the primary process.

Torrefaction gases are typically dilute with respect to combustible components leading to low flame temperatures; and in practice it might not be feasible to produce the steam of required specifications using this source alone. It is seen however that both the quality and the total quantity of heat that can be obtained from torrefaction gases increases with higher torrefaction temperatures. At the highest temperature, we see that the heat obtained from torrefaction gases can potentially provide all the energy required by the process. In design of standalone torrefaction units, it might hence be beneficial to operate at this point for the purpose of having an improved process heat source. However, with an integrated torrefaction system, it may be possible to use the torrefaction gases as a supplementary fuel in the primary process producing waste heat allowing us to conveniently use a higher quality heat source for torrefaction. Not relying on torrefaction gases to provide process leads allows us to operate the torrefaction system at energetically optimum conditions.

As can be seen from Table 4, Cycle Tempo® also calculates the U*A factor (used in heat exchanger design) on the basis of the temperature differences and heat transfer. It can be seen that the U*A product in the case of the LT Heat Exchanger much higher than the other two cases, principally implying the heat exchanger with the highest load is also proportionately larger in heat exchange area and/or has a much improved heat transfer coefficient. Fulfilling either of these requirements typically represent a high investment cost, thus making the low temperature heat exchanger a critical component in design.

5. Conclusions

A torrefaction system has been modelled by incorporating the results of externally programmed unit operation models into Cycle Tempo®. It is established that drying is the most energy intensive operation in the torrefaction process with the LT heat exchanger serving as the main site for external heat input to the system. From the point of system efficiency, lower torrefaction temperatures were found to result in a better performance with improved calorific values not found to energetically compensate for greater solid mass loss.

Acknowledgements

The authors gratefully acknowledge the financial support from E.ON Benelux in the framework of Project ‘Energy from Biomass’. We also acknowledge the work carried out by graduate student Winoi Dorai in programming the unit operation models used in the simulations.

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